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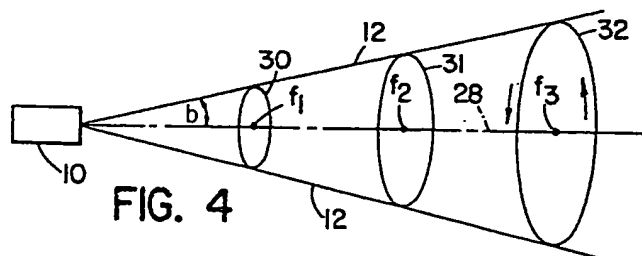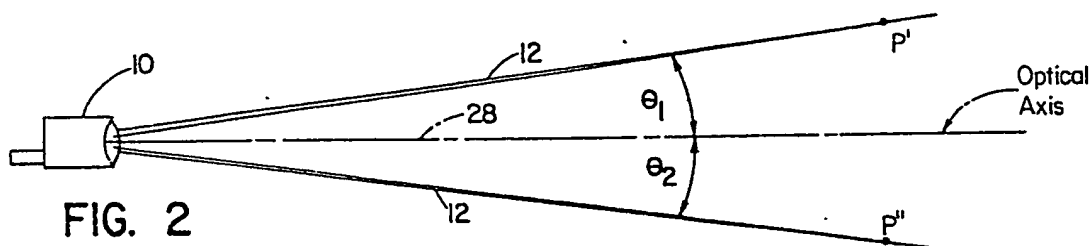
(51) INT CL^4
G01S 17/88

(52) Domestic classification (Edition I):
H4D 710 72X 745 751 753 755 756 758 783 788 L
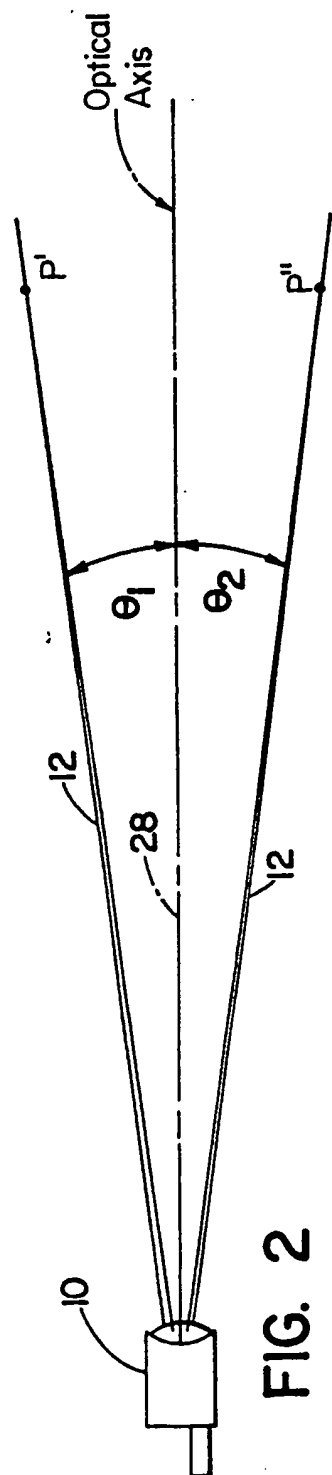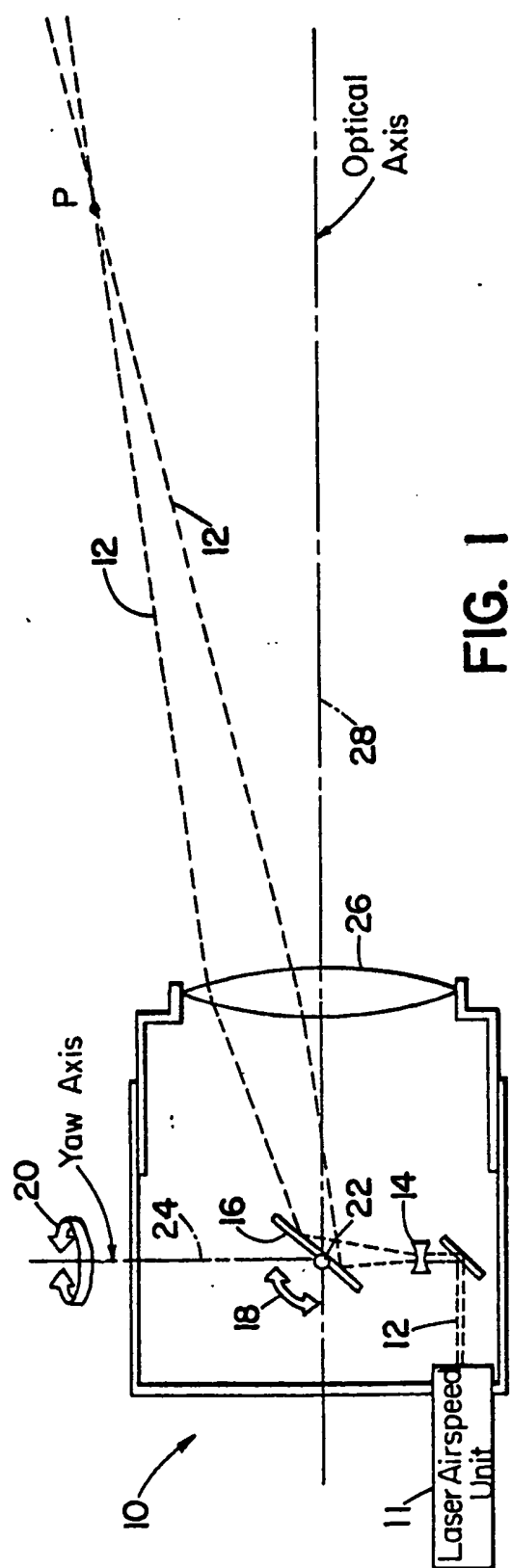**U1S 1259 1839 1840 H4D**

(56) Documents cited
GB A 2123240   **US 3984686**

(58) Field of search
H4D
Selected US specifications from IPC sub-classes G01S G01P

(54) **Gust detection system**

(57) Air turbulence ahead of an aircraft is determined by scanning the beam of a variable focal length laser airspeed unit close-in to the aircraft to determine aircraft airspeed and angle of attack, and scanning the beam at distances farther out from the aircraft and measuring airspeed. Discrepancies between the close-in measurement and the farther out measurement are taken to be indicative of air turbulence.

FIG. 2

FIG. 4

GB 2 176 965 A

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

Scan 2

Uniform Up-Gust

Scan 1

Flight
Direction

Scan 1

Scan 2

V_i

15

O

$(\theta + a)$

-15

Additional Scans to Define Vortex

Initial Scan in Plane of
Symmetry

Vortex

FIG. 13

Scan 2

Scan 1

Flight
Direction

Uniform Head-On

Scan 2

Scan 1

V_i

-15

0

15

$(\theta + a)$

FIG. 11

Scan 3

Scan 2

Scan 1

Flight
Direction

Typical Vortex
Velocity Profile

Vortex
Tangential
Velocity

Radius from Vortex Center

Direction of
Vortex Spin

Vi

O

(θ + α)

Scan 1
Scan 2
Scan 3

FIG. 12

SCAN NEAR
AIRCRAFT

CALCULATE
V_0, a, B

CALCULATE FLIGHT
PATH TRAJECTORY

ADJUST SCAN CENTER

ADJUST SCAN FOCAL DIST

SCAN AT INCREASED DIST

COMPARE WITH 1st SCAN,
CALCULATE GUST ENVIRONMENT
AT NEW DISTANCE

(REPEAT AS REQUIRED)

PILOT DISPLAY,
VORTEX ALERT

CALCULATE CONTROL INPUTS
TO NEUTRALIZE ONCOMING GUST

MAKE CONTROL INPUTS
TO AUTOMATIC STABILITY
SYSTEM

FIG. 14

SPECIFICATION

Gust detection system

5   *Technical field of the invention*   5
The invention relates to techniques for detecting gusts and windshear ahead of an aircraft.

Background of the invention
Clear air turbulence can occur either naturally or as a result of the passage of aircraft which leave vortex trails
10 and downwash patterns. Encountering such phenomena in a highly responsive aircraft can cause undesirable   10
buffeting, load factor problems, etc., despite the existence of Stability Augmentation Systems (SAS). Not only
is such unpredictable aircraft response distracting from a pilot or passenger's point of view, but it can also
affect the weapon aiming/delivery capability of military aircraft.
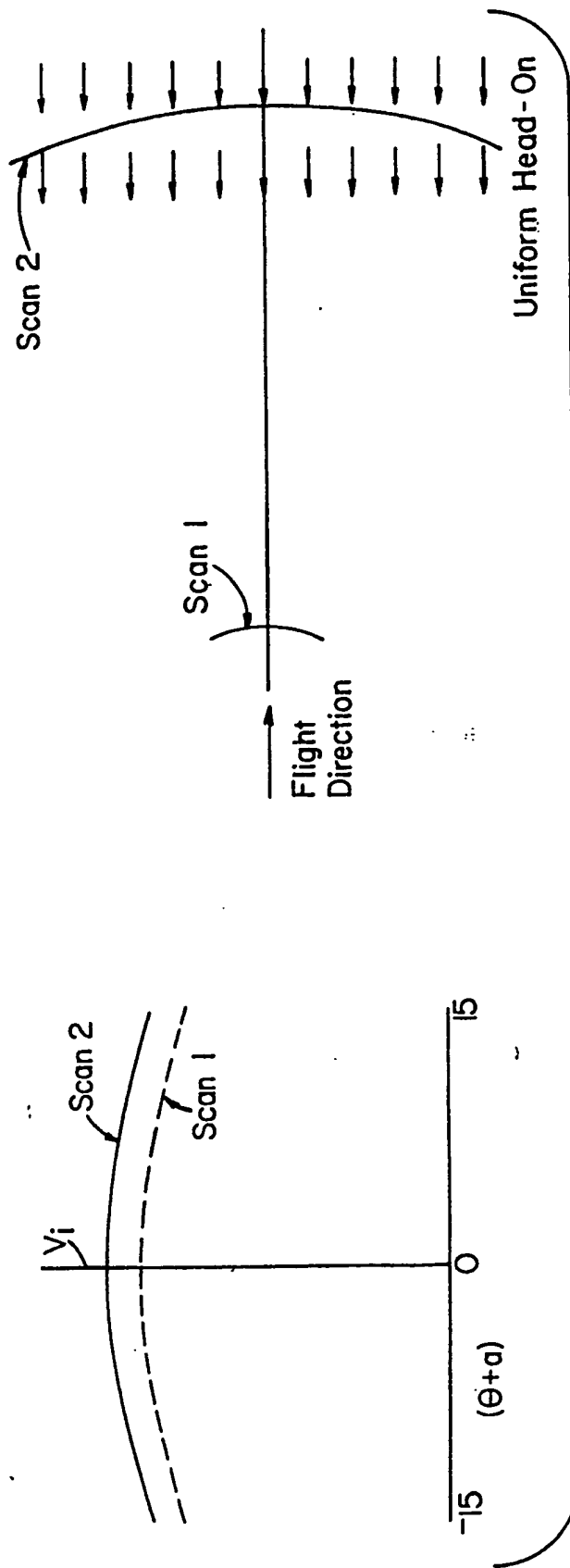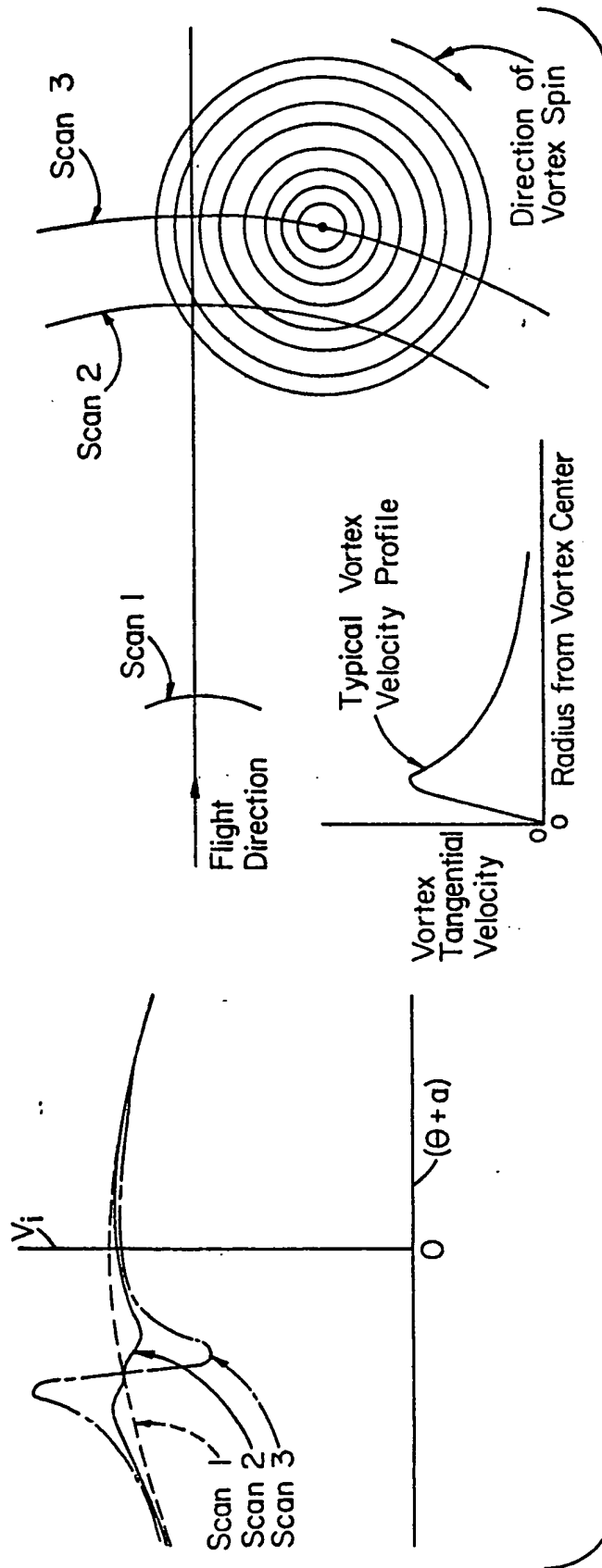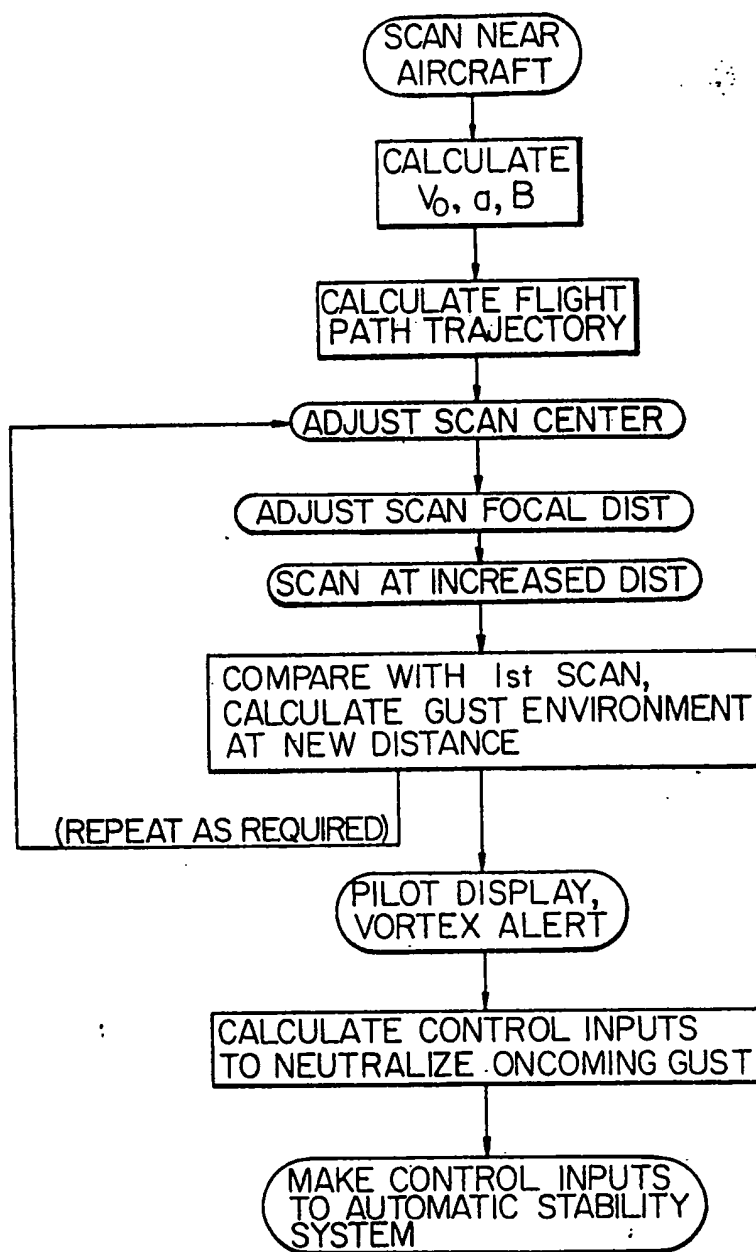
15 *Disclosure of the invention*   15
Therefore, it is an object of the invention to provide a technique for detecting clear air turbulence, thereby
enhancing aircraft safety, smoothness, and stability.
According to the invention, air turbulence ahead of an aircraft is determined by scanning the beam of a
variable focal distance laser airspeed unit close-in to the aircraft to determine aircraft airspeed and angle of
20 attack, and scanning the beam at distances farther out from the aircraft and measuring airspeed. Discrepancies 20
between the close-in measurement and the farther out measurement are quantifiably indicative of air
turbulence.
Other objects, features and advantages of the invention will become apparent in light of the following
description thereof.
25   25
Brief description of the drawings
Figure 1 is a schematic highlighting the basic elements of the gust detection system of this invention. The
system emits a scanning beam 12.
Figure 2 is a schematic of the beam scanning in elevation.
30 *Figure 3* is a vector diagram of the beam scanning in elevation.   30
Figure 4 is a schematic of the beam scanning conically at a fixed apex angle, at various distances ahead of
the system.
Figure 5 is a schematic of the beam scanning conically at a variable apex angle, at various distances ahead of
the system.
35 *Figure 6* is a schematic of the beam scanning in a cruciform scan pattern, at various distances ahead of the 35
system.
Figure 7 is a schematic of the beam scanning in elevation only, at various distances ahead of the system.
Figure 8 is a graph and schematic of the measured velocity components for a continuous vertical scan for
calm air or near in to the system.
40 *Figure 9* is a replot for the conditions of Figure 8 using a different reference.   40
Figure 10 is a graph and schematic of two scans; one close in, and another more distant scan in a region
wherein there is a uniform up-gust.
Figure 11 is a graph and schematic of two scans; one close in, and another more distant scan in a region
wherein there is a uniform head-on gust.
45 *Figure 12* is a graph and a schematic of three scans; one close in, and two more distant scans in a region 45
where there is a vortex. Another graph shows the vortex velocity profile.
Figure 13 is a plan view schematic of the beam scanning in various vertical planes at different azimuths.
Figure 14 is a gross operational block diagram for the general case of operation of the gust detection system
of this invention.
50   50
Best mode for carrying out the invention
It is known to monitor clear air turbulence (CAT) in an aircraft's flight path by projecting a laser beam in the
flight path of the aircraft and detecting the backscattered radiation from atmospheric aerosols. For instance,
U.S. Patent No. 4,359,640 (Geiger, 1982), entitled CLEAR AIR TURBULENCE DETECTION, shows such a system
55 which is limited, however, to using a pair of pulse lasers for generating a pair of coherent beams arranged to 55
converge at a point in front of the aircraft's flight path (claim 1, therein).
In commonly-owned U.S. Patent No. 4,340,299 (Mongeon, 1982), entitled OPTICAL DOPPLER RADAR
SYSTEM USING A CONICALLY SCANNED LASER BEAM, a laser of a first frequency is conically scanned on a
surface from an elevated position and the beam is scattered by the surface. A return beam is formed from this
60 scattered beam and is mixed with a single side band suppressed carrier laser beam at an offset frequency,   60
producing an electrical signal whose frequency shifts from the offset frequency in proportion to the velocity
relative to the surface. That shift is a function of the scan position and the direction of movement. Velocity
components of the signal reflecting drift velocity and heading velocity are resolved from this signal by
referencing it to the scan position at drift and heading positions. The signal component reflecting elevation
65 velocity is resolved by removing those scan dependent components. The scanning system and signal   65

processing techniques of the Mongeon Patent are especially well-suited to the present invention.

Figure 1 shows the basic configuration for the gust detection system 10 of this invention.

A laser airspeed unit 11 projects a laser beam 12 through a diverging lens 14 to a scanning mirror 16. The scanning mirror is operated by mechanisms (not shown) which will tilt the mirror in the directions shown by
5 the arrows 18 and 20, about the aircraft pitch axis 22 for elevation scan, and about the aircraft yaw axis 24 for aximuth scan. A focusing lens 26 is movable along an optical axis 28, via a suitable mechanism, to converge the beam 12 at a point P, a desired distance in front of the aircraft; for example, between 10 and 100 meters.

It is preferable to use a pulsed laser, rather than a continuous wave type in the Laser Airspeed Unit. A pulsed laser allows for lighter weight and lower power, and distance to the reflecting aerosols is simply a matter of
10 measuring the time delay between a transmitted and subsequent reflected pulse. With either type of laser, the doppler shift of the reflected beam converts directly to aircraft velocity relative to the aerosol "target". The laser airspeed unit 10 contains the necessary circuitry for resolving distance and relative velocity, in a known manner.

To determine the resultant velocity vector between the aircraft and the aerosol target it is necessary to scan
15 the beam in both elevation and azimuth. Figure 2 illustrates how the beam might be aimed in two successive elevations: an angle θ_1 above the optical axis 28 converging at point p' and an angle θ_2 below the optical axis 28 converging at a point p". This provides two components of velocity: V_1 measured parallel to the upper beam V_2 measured parallel to the lower beam. The resultant velocity R and its angle of attack (a) to the optical axis 28 are determined by the vector diagram in Figure 3 and the following equations.

20
$$V_1 = R \cos(\theta_1 + a)$$
$$V_2 = R \cos(\theta_2 - a)$$

A similar procedure, requiring at least two azimuthal positions of the beam, is followed to establish the lateral
25 component of velocity which may be represented as a sideslip angle. In practice, a continuous sweep in elevation and azimuth, such as a conical sweep, is more likely to be used than discrete points.

The Figure 3 vector diagram assumes that the velocity vectors V_1 and V_2 are measured at two points sufficiently close together so that the true total velocity vector has the same magnitude and direction at each point. In still air (no turbulence) this will be generally true, but in gusty air it will not be generally true. If the air is
30 scanned quite close to the aircraft (10 meters), the assumption of the same total velocity at the two points, or over the scanned region, will be valid for most practical purposes. Thus, it is advisable to scan close to the aircraft to measure the aircraft true airspeed (velocity, angle of attack, and sideslip angle). Gust information is then obtained by scanning at additional distances farther from the aircraft.

Many scanning patterns are possible; some possible patterns are illustrated in Figures 4-7.
35 Figure 4 shows the scanning pattern that would result from adapting a variable focal distance focusing lens to a gust detection system having a fixed conical sweep angle. The fixed apex angle (b) of the conical sweep results in larger circles 30-32 as the focal distance (f_1, f_2, f_3) is increased, a disadvantage if it is desired to detect fine structure of the air turbulence at considerable distance from the aircraft.

Figure 5 shows another conical scanning pattern with a variable apex angle. This feature can be used to keep
40 the diameter of the swept circles 34-36 constant with distance, for alternately can provide multiple sweeps of varying diameter at given focal distances (f_1, f_2, f_3) from the aircraft.

Figure 6 shows a cruciform scan pattern, where independent sweeps in vertical and horizontal planes are made at each focal distance (f_1, f_2, f_3) of interest.

Figure 7 shows a scan in the vertical plane only. For most gust situations of interest, the aircraft responds
45 primarily in the pitch axis, or plane of symmetry; the response to lateral gust inputs is generally much less and therefore of less interest.

The measured velocity componets for a continuous vertical scan for various possible atmospheric conditions are shown in Figures 8 through 12. It is assumed that lateral velocity components are small enough to be neglected. If the indicated velocity V_i is plotted versus the laser beam angle θ, measured with respect to the
50 optical axis, positive upward, the general shape of the curve will be as in Figure 8 if the air is calm or if the scan is close to the aircraft. V_o is the magnitude of the peak of the curve, which occurs at $\theta = -a$, where a is the angle of attack of the aircraft with respect to the optical axis. The value of V_i will vary according to the formula $V_i = V_o \cos(\theta + a)$. The peak of the curve will be on the left if the angle of attack of the optical axis is positive, i.e. aimed above the flight path.

55 If the curve of Figure 8 is replotted as V_i versus $(\theta + a)$, the curve becomes symmetrical about the vertical axis of the plot, as shown in Figure 9. This still represents the calm air case, or the case for a scan close to the aircraft on a turbulent day.

Figure 10 shows the results of two vertical scans when the more distant scan is in a region with a uniform up-gust having a velocity V_{gust}. Scan 1, near the aircraft, produces an indicated velocity profile identical in
60 character to that shown in Figure 9, according to the formula $V_i = V_o \cos(\theta + a)$. Scan 2, distance from the aircraft, produces a velocity profile which increases the indicated speed for beam angles below the flight path, i.e. $(\theta + a)$ negative, and decreases the indicated speed for beam angles above the flight path, i.e. $(\theta + a)$ positive, according to the formula,

The incremental speed is minus the gust velocity times the sine of the angle $(\theta + a)$.

Figure 11 shows comparable results for an oncoming head-on gust having a velocity V_{gust}. Scan 1, near the aircraft, is determined according to the formula,

5      $$V_i = V_o \cos (\theta + a);$$ 5

and Scan 2, distant from the aircraft, is determined according to the formula,

$$V_i = (V_o + V_{gust}) \cos (\theta + a).$$

10   10

In this case the shape of the indicated velocity profile is unchanged but the magnitudes are increased by a constant percentage.

Any uniform gust situation can be represented as some combination of vertical and horizontal gusts, so that the equations related to Figures 10 and 11 may be used to derive the two gust velocity components. In practice,
15 the data will show scatter and will not follow the ideal profiles precisely. Standard curve-fitting techniques can   15
be used to establish the principal gust velocity components, and the magnitude of the scatter will correspond to a general turbulence superimposed on the principal gust.

One type of departure from a uniform gust that is of particular interest is the presence of a trailing vortex produced by an aircraft having flown past the vicinity. Trailing vortices, usually found in pairs, are characte-
20 rized by relatively small size, high velocities around the core, and a life up to several minutes, depending on a   20
number of factors. Because of their intensity they can sometimes represent a serious gust encounter to be avoided. They also provide evidence of the previous passage of another aircraft, and so can provide important intelligence information in a military engagement.

Figure 12 shows indicated velocity profiles represented of a vortex crossing below the flight path of the
25 scanning aircraft. As in previous examples, the Scan 1 is close to the aircraft. The Scan 2 detects the presence   25
of a vortex, revealed by the characteristic nonlinear departure of the indicated velocity from the Scan 1 profile. By further adjustment of the beam focal distance, it is possible to locate the core of the vortex; this will be a scan with the largest indicated velocity deviation from the Scan 1 profile. Scan 3 of Figure 12 goes through the center of the vortex, and the indicated velocity profile for Scan 3 shows the large local disturbance around the
30 vortex core, which is centered about the vortex core, which is centered about the elevation at which the   30
velocity profile crosses the Scan 1 profile.

Figure 13 illustrates how the ability to alter the azimuth of the scanning beam can be utilized to locate a vortex in three dimensions. This shows an aircraft in plan view, initially scanning vertically in the plane of symmetry (in and out of the drawing). Once a vortex is detected, additional scans in vertical planes with
35 various azimuth orientations can be used to locate the center of the vortex as a line in three-dimensional space.   35
The operation of the Gust Detection System is illustrated in block diagram form in Figure 14. A verbal description on the operation of the system for the general case is as follows:

(a) Conduct a circular or cruciform scan with the laser airspeed sensor close to the aircraft. Calculate the velocity vector V_o relative to the aircraft reference axis, including angle of attack a and sideslip angle B.
40   (b) (Optional) Calculate rate of climb by calculating component of velocity perpendicular to the horizontal   40
plane, which is determined by reference to standard inertial attitude devices.

(c) From velocity, angle of attack, and sideslip measurements, along with independent measurements of body linear and angular acceleration calculate near-term flight path trajectory.

(d) Adjust the center of the scan to coincide with the projected flight path; increase the focal distance of the
45 laser airspeed unit, and scan in the desired pattern at the increased distance.   45

(e) Compare the results of the new scan with the initial scan close to the aircraft, and calculate the gust velocities at the new distance.

(f) Repeat steps d. and e. as desired to provide more complete information about the air volume into which the aircraft is flying.
50   (g) Transmit derived gust data to a pilot warning display and to a digital automatic flight control system,   50
where stored information on aircraft dynamic characteristics is used to determine aircraft control system displacements required to neutralize the oncoming gust.

(h) As the aircraft encounters the gust, input the control displacements to minimize the disturbance.

(i) (Optional) If an indicated velocity profile from any scan shows the characteristics of a vortex from another
55 aircraft, conduct additional vertical scans at different focal distances to locate core, and then conduct similar   55
vertical sweeps at other beam azimuth angles off flight path to define the vortex in three dimensions.

The scanning frequency has not been mentioned above. The appropriate frequency is dependent on the speed of flight; a high speed airplane will fly into a nearby gust more rapidly than a helicopter flying slowly in the nap of the earth. It will usually be desired to have at least a one-second warning to allow for computation
60 time with an on-board computer and to activate the controls. The laser beam travels at the speed of light and   60
the computations are very rapid. The scanning mechanism and focal length changes involve relatively low inertias; with modern servo actuators a scan should be possible in 1/20 second or less and a complete cycle with multiple focal distances should be possible in less than one-half second, and a complete update should be possible two times per second or faster.
65   The control inputs provided by the Gust Detection System (see Figure 14) are conveniently provided to an   65

automatic Stability Augmentation System (SAS) having high rates and low authority. Typically the rate, or gain, of such a system is either fixed, varied with airspeed, or varied by means of an adaptive controller. This is discussed in detail in commonly-owned U.S. Patent No. 4,032,083 (Maciolek, 1977), entitled AUTOMATIC GAIN CONTROL FOR STABILITY AUGMENTATION SYSTEMS, which discloses a technique for automatically
5   varying the gain of a SAS in accordance with gross weight and deviations of the center of gravity of the aircraft.   5
      To practice the invention in the context of a SAS as disclosed in the Maciolek Patent, the control inputs could be provided to close the switches 50, 54, 56 therein which vary the gain of the SAS in stepwise fashion.
      In another commonly-owned U.S. Patent No. 4,213,584 (Tefft et al., 1980), entitled HELICOPTER HOVER STABILITY AND CRUISE GUST EFFEFCT ALLEVIATION it is disclosed to vary the SAS inputs according to
10 airspeed.   10
      Thus, it can be seen that there are many ways in which the control inputs of this system can be utilized, in conjunction with an existing SAS so that oncoming gust effects can be both anticipated and alleviated.
      It should be understood that various changes may be made to the invention without departing from the spirit and scope thereof.
15   We claim: 15

CLAIMS

      1.   A method of detecting air turbulence in the flight path of an aircraft comprising:
20   providing a variable focal distance laser airspeed unit in the aircraft to project a beam ahead of the aircraft at   20
      various focal distances;
        measuring the airspeed close to the aircraft at at least two points to determine the velocity (V_o) and angle of attack (a) of the aircraft relative to still air;
        measuring the airspeed at a distance further ahead of the aircraft; and
25   determining that there is air turbulence at the distance further ahead of the aircraft based on a discrepancy   25
      between the measured airspeed close to the aircraft and the measured airspeed at the distance further from the aircraft.
        2.   The method of claim 1, further comprising scanning the beam in a circular pattern ahead of the aircraft to measure the airspeed, wherein the diameter of the circles increases with the distance from the aircraft.
30   3.   The method of claim 1, further comprising scanning the beam in a circular pattern ahead of the aircraft to   30
      measure the airspeed, wherein the diameter of the circles remains the same with the distance from the aircraft.
        4.   The method of claim 1, further comprising scanning the beam in elevation only to measure the airspeed.
        5.   The method of claim 1, further comprising scanning the beam in azimuth only to measure the airspeed.
        6.   The method of claim 1, further comprising scanning the beam in a cruciform pattern ahead of the aircraft
35   to measure the airspeed.   35

PN - SU1023240 A 19830615
TI - WIND SPEED TWO-COMPONENT PHOTOELECTRIC METER
PA - FEDOTOV BORIS N
IN - FEDOTOV BORIS N
AP - SU19813290632 19810518
PR - SU19813290632 19810518
DT - I

AN - 1984-081170 [37]
TI - Two-component photoelectric WIND SPEED indicator - has step motor to rotate perpendicular plates on gearwheel

AB - SU1023240 Indicator has advantage of improved accuracy in measuring the vector of the WIND SPEED in maritime conditions, achieved by inclusion of a drive unit in the meter, kinematically connected to the gearwheel, fastened on the axis of rotation of the vane.
- The light flow from source (1), through hollow tube (3) and reflectors (7,10) is directed onto photo-detectors (4,5). The period of shadowing depends on the rotation angle of the vane (2) and the positions of plates (8), characterising magnitude of the component of the SPEED vector in orthogonal axes, one of which coincides with the diametral plane of the SHIP. The number of impulses shaped by reflector (10) characterises the WIND SPEED. The magnitudes of the components are summed during a time interval, using step motor (12) to rotate Plates (8), through gearwheels (6,9). Components of the SPEED vector are determined, according to time intervals between moments of formation of impulses by the detectors. Bul.22/15.6.83.
- (3pp Dwg.No.1/2)

IW - TWO COMPONENT PHOTOELECTRIC WIND SPEED INDICATE STEP MOTOR ROTATING PERPENDICULAR PLATE GEAR
PN - SU1023240 A 19830615 DW198413 003pp
IC - G01P5/06
MC - S02-G01A S03-D
DC - S02 S03
PA - (FEDO-I) FEDOTOV B N
IN - FEDOTOV B N
AP - SU19813290632 19810518
PR - SU19813290632 19810518

TI - Doppler ---lidar--- measurements of wind and turbulence in the marine boundary layer

AU - Hardesty R M ; Intrieri J M

CONF- Conference Proceedings. Second Topical Symposium on Combined Optical-Microwave Earth and Atmosphere Sensing (Cat. No.95TH8015), Conference Proceedings Second Topical Symposium on Combined Optical-Microwave Earth and Atmosphere Sensing, Atlanta, GA, USA, 3-6 April 1995

IW - atmospheric boundary layer; atmospheric measuring apparatus; atmospheric movements; atmospheric techniques; atmospheric turbulence; ---laser--- applications in medicine; ---lasers---; meteorological instruments; meteorology; optical radar; wind

AW - atmosphere meteorlogy; ---laser--- remote sensing; measurement technique; ---lidar--- equipment apparatus; Doppler ---lidar---; wind; turbulence; marine boundary layer; vertical motion; stratocumulus cloud breakup; container-mounted ---lidar---; shipboard; ship

AB - Characterization of wind structure in the marine boundary layer is important for understanding the processes affecting ocean-atmosphere exchange of heat, moisture and momentum, marine stratus formation and dissipation, and emission and scattering of electromagnetic radiation from the ocean surface. Although wind information in the lower boundary layer can be obtained from balloons, anemometers mounted on ship masts, and/or radar wind profilers, Doppler ---lidars--- offer the capability of interrogating a large area segment of the marine layer from a single location with high vertical and moderate horizontal spatial resolution. Application of Doppler ---lidar--- to marine studies was first demonstrated by Banta et al. (1993), who used ---lidar--- wind measurements to illustrate the temporal and spatial evolution of the sea breeze near Monterey, CA. The present authors extend the applications to include measurements of vertical motion for better understanding of stratocumulus cloud breakup, as well as wind field characterization and the effect of winds on the radar scattering signal from the ocean surface. They also describe a new, container-mounted ---lidar--- system specifically designed for shipboard wind measurements (4 Refs.)